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ORIGINAL ARTICLE

Other ways to examine the finances behind the birth of Classical Greece

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Abstract

Although the birth of Classical Greece is often attributed to the constitutional reforms of Cleisthenes (508/507 BCE), the achievement of an economically minded government under the Peisistratid tyrant Hippias (527–510 BCE) potentially paved the way by advancing Athenian silver for exportation in international trade. It is proposed here that new silver technology, which initiated the transition from acquiring silver from 'dry' silver ores to silver-bearing lead ores, was introduced to Greece during the time of the Peisistratids (561–510 BCE). Massive exploitation of silver-bearing lead ores at Laurion in Attica, which later financed the construction of a war navy, appears evident in the lead pollution records of Greenland ice, lead isotopic analyses of sixth-century BCE Attic silver coins and late Iron Age Levantine hacksilver, and is reflected in the numbers of lead votive figurines at sanctuaries in Sparta. Against the backdrop of the threat of war with Persia and an imminent Spartan invasion which resulted in the overthrow of Hippias (510 BCE), it is considered that a political transition occurred because Greece was both geologically and politically disposed to adopt this labour-intensive silver technology which helped to initiate, fund and protect the radical social experiment that became known as Classical Greece.

KEYWORDS

democracy, economy, figurines, lead isotopes, lead pollution, silver

SILVER AND THE ATHENIANS

The transition from tyranny to the establishment of representative government was 'annoyingly unheroic', with the second-generation Peisistratid tyrant Hippias having been overthrown thanks to a

Spartan invasion of Attica in 510 BCE (Price & Thonemann, 2010: 130).

From the mid-sixth century BCE, political life in Athens had been controlled by the Peisistratid family, whose tyranny dominated public affairs, resulting not only in oppressive but also in 20 years of beneficent measures. According to Herodotus (Herodotus, 2007: 1.62.2–63.2; 1.64.1), Peisistratos (561–527 BCE) required external military support to defeat and exert control over his aristocratic opponents as well as for overseas operations including the defence of Sigeion (Herodotus, 2007: 5.94.1) and the conquest of Naxos (Herodotus, 2007: 1.64.2). He collected debts and received donations while in exile (Herodotus, 2007: 1.61.3–4; 1.62.2). Patronage of the arts and support of national festivals, along with building programmes, which included an aqueduct and the beginnings of a temple dedicated to Zeus (Thucydides, 2008: 6.54.5; Kitto, 1962: 102–106), would have been expensive.

To finance these projects, it has been assumed that Peisistratos used revenue streams that were generated from mining silver at Mount Pangaeus in northern Greece and the silver mines located closer to home at Laurion in Attica, south of Athens (Figure 1, a) (Hopper, 1968). Herodotus states that the Peisistratids were 'drawing increased revenues both from Attica itself and from the region of the River Strymon' (Herodotus, 2007: 1.64.1: trans. A.L. Purvis). However, Hopper (1968) also notes that although silver was indeed produced at Laurion during this time, the amount is unclear for the years before when a rich vein of silver was discovered at Maroneia (484/483 BCE) in the vicinity of modern Agios Konstantinos and the neighbouring region of Laurion, and that historians and researchers may have overestimated the importance of mining in the Laurion district. In effect, it is difficult to determine when Laurion contributed significantly to the finances of Athens because Athenians only regularly inscribed their financial records on stone from 454 BCE (Price & Thonemann, 2010: 124).

The timing of the Maroneia silver strike is perhaps too fortuitous for the report to be completely reliable, especially when it considered that to dig a shaft and horizontal galleries sufficiently large for workers to follow veins (Figure 1, b) of argentiferous galena (PbS) could take years before exploitation commenced; that is, an upper estimate of 9 m per month would perhaps provide an explanation to why Athenian mining leases were awarded for 10 years (Aperghis, 2013). This would suggest that the famous Maroneia discovery should be viewed not as a sudden occurrence but as the culmination of years of mining experience at Laurion resulting in a politically stimulated intensification of labour-intensive silver production, which later initiated the building of a war fleet of 200 triremes that were deployed at the battle of Salamis in 480 BCE against the Persians (Aristotle, 1952: Ath. Pol. 22.7). With the process of extracting silver from argentiferous lead ores potentially beginning much earlier than 484/483 BCE, the view that lead ores were mined at Laurion for silver by the Peisistratids in Greece's late Archaic period (Davis, 2014; Doctor & Van Liefferinge, 2010; Kroll, 1981, 2008) becomes increasingly credible.

Silver was the main metal used for Greek coinage in the second half of the sixth century BCE. Attic coinage production was vastly expanded, and coin types changed from 'Wappenmünzen' (heraldic coins) to the 'owl' toward the end of the sixth century BCE (Kroll, 1981). However, although these changes were presumably related to the exploitation of silver from Laurion, it is difficult to determine whether these changes were a consequence of the tyrants or the new democracy (Davis, 2014). Kroll (1981) suggests that the changing types were the devices of individual magistrates, notably co-opted elites, working in conjunction with the Peisistratids to oversee the production of coinage. Furthermore, he attributes Peisistratos' son Hippias (527–510 BCE) the far-reaching policy that included not only the introduction of the gorgoneion and owl tetradrachms for exporting Attic bullion but also the increased exploitation of the Laurion mines that made such export possible. This would seem plausible against a backdrop that had placed Western Mediterranean silver in Carthaginian hands and out of reach of the Greeks following the battle of Alalia (540/535 BCE) (Herodotus, 2007: 1.166; Gale et al., 1980), the depletion and probable exhaustion of the silver mines in Siphnos (*c*. late sixth century BCE) (Herodotus, 2007: 3.57–8; Pernicka & Wagner, 1985) and presumably the loss of Thraco-Macedonian silver sources after the invasion by the Persian King Darius (513/512 BCE) (Herodotus, 2007: 5.11; 5.23).

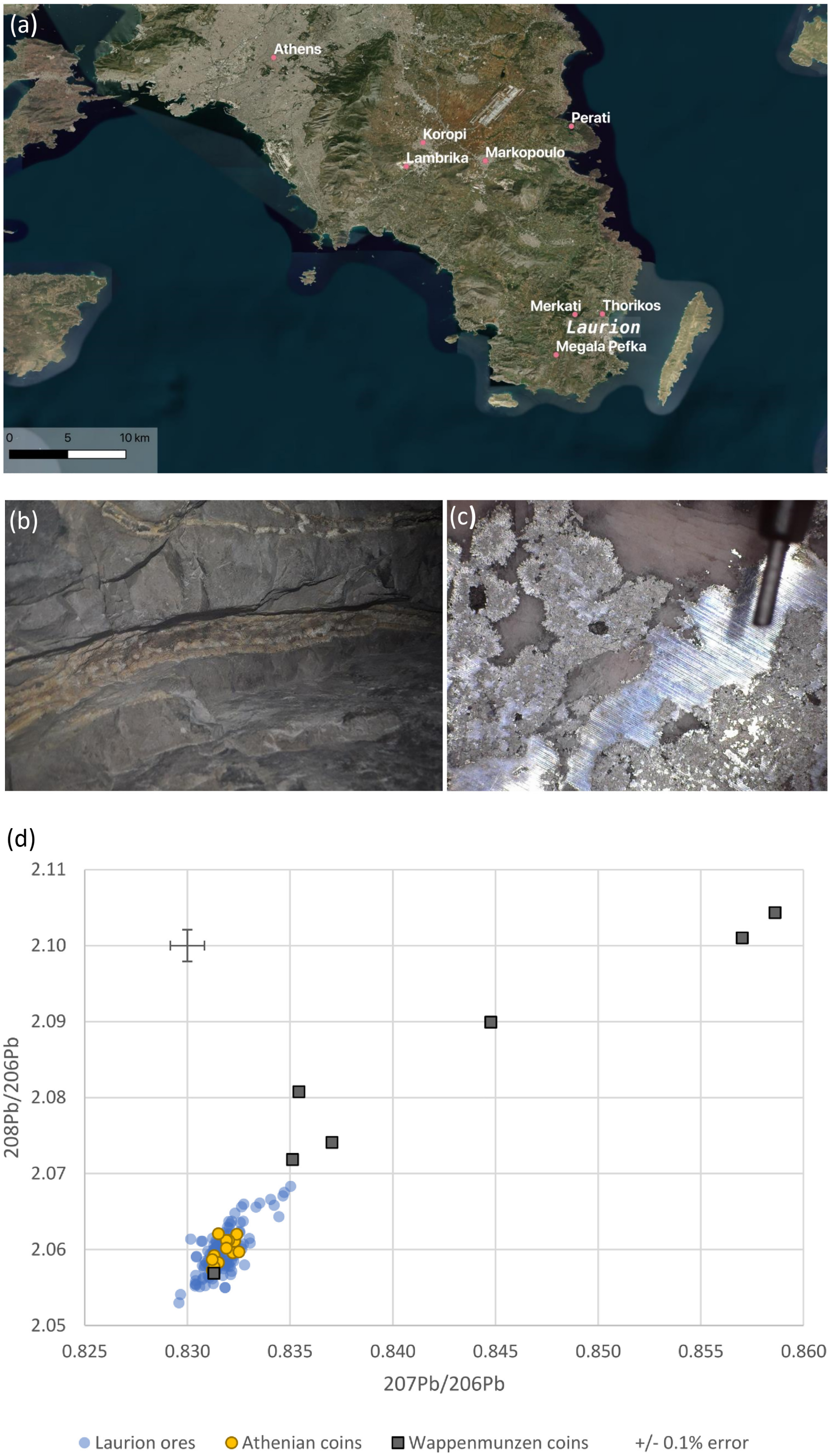

FIGURE 1 (a) Map of Attica in Greece showing the region of Laurion; (b) galena (PbS) mineral veins; (c) native silver dispersed in a lead-poor host rock; (d) lead isotope analysis (LIA) plot of Laurion ores (blue circles), Wappenmünzen coins (*c.*545–510 BCE) (dark squares) and Athenian owls from the Asyut hoard (fifth–fourth centuries BCE) (orange outlined circles) (data from Gale et al., 1980: tab. 6; and OXALID, 2022). The Athenian coins are consistent with Laurion ores. Six of the seven Wappenmünzen coins are not consistent with the Laurion ore field [Color figure can be viewed at wileyonlinelibrary.com]

This article recognizes that Laurion was potentially exploited for silver from the sixth century BCE and aims to contribute to an understanding of the transition between the Peisistratids and Classical Greece through the examination of silver and lead, using types of data that are not usually presented together.

It is contended here that the birth of Classical Greece can be identified as when a change in silver extraction technology appeared at Laurion in Attica. This rather unqualified statement would seem to ignore that a sense of 'Greekness' (Price & Thonemann, 2010: 109) had been emerging throughout the late seventh and early sixth centuries BCE due to new threatening powers on the eastern horizons of the Greek world. However, it is proposed here that the exploitation of lead ores for their intrinsic silver at Laurion, which swelled the Athenian coffers in the absence of other sources of silver, was intimately connected to this growing identity, as it would have required organization, regulation and perhaps the import of labour to release the commodity that would boost taxable trade and commerce. Moreover, such a new sector of wealth would have likely disrupted the dominance of the 'old agriculturally-wealthy elite' in politics and law (Davis, 2014: 277). In effect, the constitutional reforms of Cleisthenes (508/507 BCE), which were set in motion only a few years after the exile of the tyrant Hippias (510 BCE), potentially arose due to the presence of the Persians and Spartans on Greek territory *and* the exploitation of silver-bearing lead ores at Laurion that had placed Athens on an international stage (Kroll, 1981) and was later to fund and protect the representative government of the world's first democracy.

TRANSITION TO SILVER-BEARING LEAD ORES

Conventional wisdom holds that argentiferous lead ores were the main source of silver in antiquity (e.g., Forbes, 1950: 180; Gale & Stos-Gale, 1981a, 1981b; Legarra Herrero, 2004; Meyers, 2003; Moorey, 1994; Pernicka & Bachmann, 1983; Stos-Gale & Gale, 1982; Strong, 1966: 3). This seems to have been the case at Laurion, at least from the mid-first millennium BCE. Installations at the site (e.g., washeries), slag heaps (deriving from argentiferous lead ores), historical records and coinage (such as Athenian coins; e.g., Gale et al., 1980) all attest to intensive silver production at the site (e.g., Ellis Jones, 1982; Healy, 1978; Hopper, 1968; Rehren et al., 2002).

The technology to extract silver from argentiferous lead ores is remarkable for several reasons. Unlike smelting lead ores (which generates lead metal and lead slag), the extraction of silver from argentiferous lead ores always requires the additional cupellation step (which generates silver and litharge) to separate the low amounts of silver that have partitioned into the lead metal during smelting argentiferous lead ores. However, it is very difficult to tell a priori how much silver, if any, there is in a lead ore (Zhou, 2010) such as the galena ores at Laurion, to warrant conducting this additional step on the lead metal; that is, concentrations of silver in argentiferous lead ores are invisible to the naked eye. In fact, extracting silver from lead ores in this manner would make it the first example of invisible trace amounts of one metal being separated from another. Gale and Stos-Gale (1981b: 217) advocated that test smelts were conducted by ancient silver producers on lead ores followed by cupellation of the lead produced. This mechanism was used to explain the absence of lead ores, but the presence of litharge with Laurion lead isotopic signatures, at Bronze Age sites such as those on the islands of Siphnos, Seriphos, Kea and Thera (Gale & Stos-Gale, 1981b), Limenaria on Thasos (Papadopoulos, 2008), and at Koropi, Lambrika and Markopoulo in Attica (Kakavogianni et al., 2008); that is, argentiferous lead ores (Forsyth, 1997) or lead metal were considered to have been transported for subsequent processing to areas that did not have argentiferous lead ore deposits of their own. It should also be noted that lead smelting slag is generally absent at Bronze Age sites where litharge has been recovered, not only in Greece but also in Anatolia, Syria (Hess et al., 1998; Pernicka et al., 1998) and Iran (Nezafati & Pernicka, 2012; Weeks, 2013). This would already indicate that it is unlikely that lead ores were transported for subsequent smelting at other locations.

This test-smelt scenario, however, would further imply that smelted lead could have been divided into lead and silver-bearing categories – a difficult task when silver concentrations are at trace levels— to make lead and silver objects. Moreover, to produce 1 kg of silver from even the most argentiferous of lead ores at Laurion (4760 ppm Ag) would require a substantial amount of lead (at least 210 kg of argentiferous ores or 169 kg of smelted lead) (Wood et al., 2021). These weights would clearly have implications regarding the transport of ores or lead metal for subsequent processing at sites where litharge has been located. Furthermore, not only are finds of litharge often not located near argentiferous lead ore deposits, but also galena is found in the primary sulfidic ore body below the oxidized zone and close to the water table (Gale & Stos-Gale, 1981b: fig. 1; Gale, 1980: 163; Meyers, 2003: 271–88), thereby requiring the application of technology associated with deeper mining. This would suggest that even if galena had been recognized as a silver source from the earliest times, lead ores would not have been particularly attractive to the ancient prospector. In fact, Gale and Stos-Gale (1981a) noted that of the 31 regions of lead-silver mineralization they studied around the Aegean, many were probably not worked in the Bronze Age and some not even in Classical times.

In effect, the labour-intensive stages of prospecting, mining, beneficiating and smelting large quantities of argentiferous lead ore, followed by cupellation, would have required industrialization of the process in order to make it worthwhile. This is particularly pertinent when it is considered that Bronze Age litharge is often found in domestic contexts, such as such as the private house at Thorikos, House A in rooms 30 and 39 on Ayia Irini, the ‘unexplored mansion’ on Crete, the West House in the room of the fisherman at Akrotiri, and at the Mousia farmhouse on Siphnos (Mussche, 1974: 44–66; Wood et al., 2021). This would support that the process of smelting and cupellation was potentially conducted at a much smaller scale than the later industrial processes associated with the extraction of silver from galena ores. Even accepting that absence of evidence is not evidence of absence, the paucity of Bronze Age litharge (Gale & Stos-Gale, 1981b; Kassianidou & Knapp, 2005: 220) and slag (e.g., Kakavogianni et al., 2008; Papadopoulos, 2008) around the Aegean and further afield (Hess et al., 1998; Nezafati & Pernicka, 2012; Pernicka et al., 1998; Weeks, 2013) is inconsistent with the level of production required to make the exploitation of argentiferous lead ores viable. This is the case irrespective of whether the Bronze Age silver prospectors were aware of the levels of silver in these ores which, as already mentioned, are invisible to the naked eye.

By relegating the acquisition of silver from lead ores to the introduction of industrial-scale processing, necessarily implies that silver objects before this advancement must have derived from other silver sources. It is not controversial to say that silver minerals (native silver, large silver minerals, such as horn silver AgCl, argentite Ag_2S and so forth) were used to produce silver objects before the exploitation of lead ores. However, it must also be recognized that silver is present in dry silver ores (Figure 1, c); that is, native silver and/or silver minerals in the form of dendrites, grains, scales and tiny groups of crystals dispersed in lead-poor rock, such as quartz (Bastin, 1922; Patterson, 1971). Silver-bearing minerals in dry silver ores are often visible to the naked eye as inclusions. For example, the ores of Siphnos, which occur in a gossan, do not have a particularly promising appearance, although compounds containing silver are often distinguishable as yellow ore inclusions (Gale & Stos-Gale, 1981b). Nonetheless, for lead-poor ores, the rocky matrix needs to be crushed and molten lead added as a silver collector, followed by cupellation of the lead metal, for the silver to be extracted. This process was described in treatises by Pliny the Elder in the first century CE, and by Agricola and Erker in the 16th century CE (Wood et al., 2021). Moreover, despite proposing that lead ores, especially galena, were the chief source of silver in antiquity, Stos-Gale and Gale (1982: 467 n. 1), the main champions of lead isotope analysis (LIA), also recognized: ‘It is very probable that lead would also have been very largely used in the production and purification of silver from native silver or the dry silver ores such as argentite and cerargyrite.’

Archaeological evidence for the addition of lead to extract silver from lead-poor ores can be found in Phoenician and Roman Iberia during the first millennium BCE (Anguilano et al., 2009; Murillo-Barroso et al., 2016; Wood et al., 2019, 2020; Wood & Montero-Ruiz, 2019). Moreover, the process seems to have originated further East. In Bronze Age Anatolia and northern Syria, lead is found in association with slag and litharge. The lead metal recovered at Habuba Kabira in Syria (Pernicka et al., 1998), a site which has been identified as a possible location for the origin of cupellation (^{14}C dating determined a late Uruk period date of *c*.3300 BCE; Pernicka et al., 1998) has a silver concentration of 232 ppm. This low value would suggest that the lead was probably not used for its intrinsic silver. Moreover, the hazelnut-sized slag from Fatmali-Kalecik in East Anatolia not only looks similar to that found at Siphnos but also has silver-metal inclusions (Hess et al., 1998: fig. 5) with Au/Ag × 100 of 1.26. This indicator (which, due to its chemical inertness, can survive smelting and cupellation) does not suggest the smelting of argentiferous lead ores (which generally have Au/Ag values around two orders of magnitude lower) to argentiferous lead (Wood et al., 2021), but rather the reduction of silver minerals ores (with their higher Au/Ag ratios) to silver by crushing rock and heating the mixture in the presence of lead, followed by cupellation. A similar argument can be made for the higher Au/Ag values in litharge than the associated lead at Thorikos in Laurion and on the Aegean Island of Kea (Wood et al., 2021: tab. 7); that is, the barely argentiferous lead recovered was more likely to have been used as a silver collector for dry silver ores rather than as a source of silver in its own right.

As with Siphnian ores (which were exploited from the Bronze Age to the late sixth century BCE), the exploitation of lead-poor jarosite ores on Iron Age Cyprus would have required the addition of lead to exploit silver (Bell & Wood, 2022; Wood et al., 2021). Furthermore, the process appears to have been adapted for the seventh-century BCE Lydian practice of adding lead to recover silver from the parting vessels and furnace linings after parting silver from gold using the ancient salt cementation process (Craddock, 2000: 200–211; Wood et al., 2017a). That dry silver ores were in widespread use even as late as the early Islamic period (Merkel, 2021; see also Meyers, 2003; Wood et al., 2021) and archaeological field surveys (De Jesus, 1980; Wertime, 1968, 1973; Yener et al., 1991) support the late adoption of smelting galena for silver in Anatolia and Iran, could suggest that the labour-intensive exploitation of argentiferous lead ores for silver was practiced only in locations that had limited access to other silver sources.

Confusion in the archaeological literature over which types of ore were exploited before the mid-first millennium BCE seems to have stemmed from long-held misconceptions that silver and lead objects found in association (e.g., in graves; Klein & Hauptmann, 2016: 136) and that the presence of litharge (PbO) at metallurgical sites must implicate the exploitation of argentiferous lead ores for their trace levels of silver. However, lead and silver artefacts recovered in the same archaeological context do not necessarily imply that both metals had derived from the same mineral, and litharge would be present from cupellation of lead used to collect silver from dry silver ores. A major problem for archaeological science, however, is that by accepting that silver could have been extracted by adding exogenous lead, provenance investigations can be frustrated; that is, if the lead used to collect silver derived from a different geological location to the silver ore, the extracted silver will have a lead isotopic signature associated with the location of the lead ore rather than the silver source (Wood et al., 2017b). In fact, the prevalence of Laurion LIA signatures in objects and technical debris recovered around the Aegean (Wood et al., 2021) indicates that Laurion lead was the silver collector of choice. In effect, lead from Laurion (and its lead isotopic signature) may have been carried by ancient 'prospectors' to use when they encountered dry silver ores worth exploiting.

How argentiferous lead ores were eventually recognized as being a source of silver is difficult to say. Regardless of whether this knowledge was first realized at Laurion or in other regions with argentiferous lead ores, such as Thrace or Anatolia, and was subsequently transmitted to Laurion, the addition of lead to collect silver from dry silver ores potentially resulted in the recognition that lead itself could be silver-bearing. This realization may have emerged when control over silver purity became integral for coinage as a store of value in the mid-first millennium BCE (Strong, 1966: 5; Hopper, 1968; Kraay, 1976; Healy, 1978; Treister, 1996: 23); that is, as progressively lower grade dry silver ores were processed with increasingly high amounts of lead, it was noticed that the amount of silver recovered during cupellation was greater than expected, and that this 'extra' silver must have been introduced from the lead source.

There will be no unique date for the transition from prospectors targeting dry silver ores to the conscious exploitation of the trace levels of silver in argentiferous lead ores because lead-poor dry silver ores were still being exploited when it is proposed that lead ores were first mined intensively for silver at Laurion, that is, the sixth century BCE. However, the scarcity of Aegean silver objects in the archaeological record at the end of the Bronze Age (*c*.1200 BCE) (e.g., at Mycenae; Kelder, 2016: 309–319) and throughout the Early Iron Age (*c*. 12th–9th centuries BCE) (Dickinson, 2006: 119–120) potentially reflect the gradual exhaustion of dry silver ores in the East Mediterranean, which stimulated the search for similar silver ores in the West Mediterranean (Wood et al., 2021). For instance, the hacksilver hoards of the Early Iron Age southern Levant (*c*. 12th–9th centuries BCE) do not have compositional or isotopic signatures associated with argentiferous lead ores at Laurion, but with Anatolian ores and with silver-bearing jarosite ores found in the Western Mediterranean. This supports that lead ores were not exploited for their trace levels of silver at this time as well as implicating Iberia as an important source of silver (Wood et al., 2019, 2020). In fact, Phoenician expansion in Iberia (Figure 2, b) eschewed argentiferous lead ores in favour of extracting silver from lead-poor jarosite ores at Huelva (a process which continued during Carthaginian and Roman times) (Wood et al., 2021; Wood & Montero-Ruiz, 2019). This is relevant here not only because it demonstrates that the technology of extracting silver with exogenous lead crossed the Mediterranean in the first half of the first millennium BCE, but also because direct access to Iberian and Etrurian silver was cut off to the Greeks following defeat of the Phocaeans by the Carthaginians and the Etruscans at the Battle of Alalia in 540/535 BCE (Herodotus, 2007: 1.166; Gale et al., 1980). This would have made Athenian exploitation of silver at Laurion even more pressing, particularly since datable archaeological material reveals that mining in the Aegean island of Siphnos ceased in the late sixth century BCE (Herodotus, 2007: 3.57–8; Pernicka & Wagner, 1985), perhaps due to the flooding of mines mentioned by Pausanias (*X*, II.2; as quoted in Gale et al., 1980). This could have initiated exploitation of the more labour-intensive argentiferous lead ores (compared with silver minerals) at Laurion during the reigns of the Peisistratids in the sixth century BCE, in order to meet their fiscal needs.

Essentially, there appears to have been a transition in silver technology from using low amounts of lead to collect high concentrations of silver from dry silver ores to the massive exploitation of lead ores to extract their very low concentrations of intrinsic silver. This would suggest that the new technology advanced at Laurion was a consequence of new *knowledge*, that is, the recognition that lead ores were a source of silver in their own right; and the scaling up of existing *know-how* that had been used since the Bronze Age, that is, smelting and the silver-refining cupellation process.

The question that needs to be raised is therefore not whether there was a transition from using exogenous lead to extract silver from dry silver ores to the exploitation of massive quantities of lead ore for its intrinsic levels of silver, but rather when extracting silver from lead ores was adopted at Laurion. The following sections investigate when this transition could have occurred by using types of data that are not usually presented together.

ANCIENT WORLDWIDE LEAD PRODUCTION

Most emissions of pollutants to the global atmosphere occurred after the European Industrial Revolution, driven by the combination of unprecedented growth in the population of the Earth and massive technological and economic development (Candelone et al., 1995). Ancient lead production (tonnes (t) per year) has been estimated from stocks and losses of silver and copper (Patterson, 1971, 1972; Settle & Patterson, 1980) and from concentrations of atmospheric lead deposited in ice cores in Greenland (Hong et al., 1994, 1996a, 1996b; McConnell et al., 2018).

Patterson's (1972) economic approach assumes that the desire for silver in ancient times was the principal stimulus for lead production and that lead mined and smelted for lead itself has constituted a significant portion of total lead production only in modern times. This traditional view is disputed, with lead objects in the archaeological record indicating that lead ores may have been the first metal

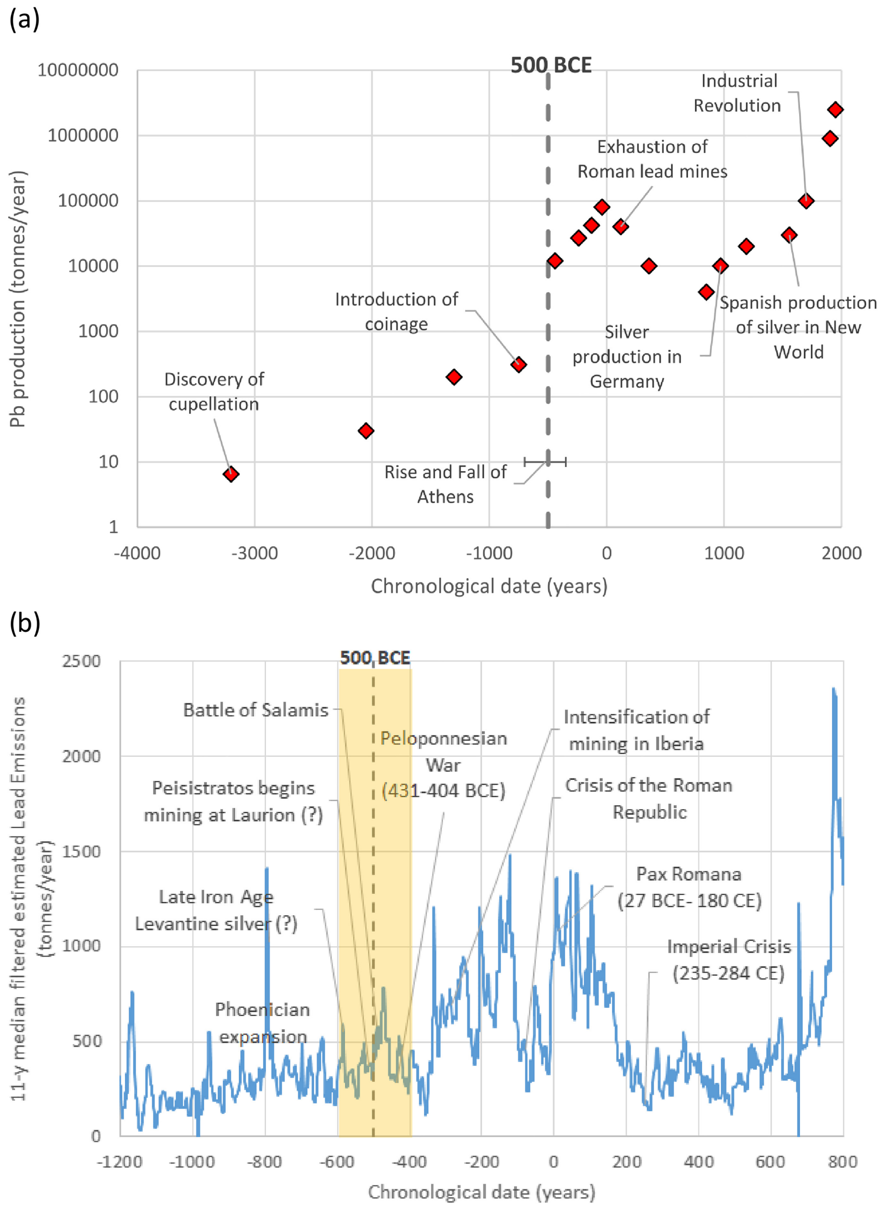

FIGURE 2 (a) World lead production (t/year) during the past 5500 years based on estimates of silver and copper production determined from stocks and variation in loss constants during different chronological periods (adapted from Settle & Patterson, 1980). (b) Estimated lead emission data (t/year) derived from ice cores in Greenland (adapted from McConnell et al., 2018). Approximate chronologies for relevant events are signposted on both plots [Color figure can be viewed at wileyonlinelibrary.com]

to be smelted, probably in the Near East or Anatolia and perhaps as early as the seventh millennium BCE (Gale & Stos-Gale, 1981a), or at least as early as the late fifth millennium BCE in the Levant (Yalahom-Mack et al., 2015). Nonetheless, Figure 2 (a) shows that world lead production increased from a few tonnes to around 160 t/year after the invention of the silver-refining process of cupellation (i.e., *c*.5200 years ago; Pernicka et al., 1998). It then rose to 10,000 t with the introduction of coinage and again to 80,000 t during the flourishing of the Roman Republic and Empire 2000 years ago. Lead production declined during medieval times, but with the onset of the Industrial Revolution, production increased dramatically from 100,000 t annually 300 years ago to 1 million t in the early 20th century.

A similar pattern to Figure 2 (a) was determined by Hong et al. (1994) based on measurements of atmospheric lead (picograms (pg)/g) deposited in 18 discrete ice-core samples between 1100 BCE and 800 CE in Greenland. More recently, McConnell et al. (2018) estimated lead emissions based on continuous measurements of lead pollution in deep Greenland ice (Figure 2, b). Their atmospheric model demonstrated that European emissions of lead (to which they attribute the bulk of lead pollution measured in Greenland) closely varied with historical events, including imperial expansion, wars and major plagues. Furthermore, lead emissions decrease in parallel with a decline in the silver content of Roman *denarius* coins (Butcher & Ponting, 2015) during the Pax Romana and the onset of the Roman Imperial crisis, reflecting the importance of lead in the acquisition of silver for the Roman economy. Figure 2 (b) is adapted from the data published in McConnell et al. (2018) who highlight events mentioned in the current article.

Absolute values of lead emissions are different on the two plots in Figure 2. However, since lead emissions from locations other than Europe are considered less likely to have been deposited in Greenland ice, perhaps by an order of magnitude (McConnell et al., 2018), it is not surprising that worldwide lead production (Figure 2, a) would be higher than the values of lead deposited in Greenland. Nonetheless, regardless of whether the assumptions behind these estimates of lead production (Hong et al., 1994; McConnell et al., 2018; Patterson, 1971, 1972; Settle & Patterson, 1980) reflect accurately the absolute amounts of lead smelted over the chronologies investigated, the two distinct approaches appear to generate similar patterns.

Of particular interest here is the increase in lead production *c*.500 BCE (dashed line in Figure 2, a, b; and shaded area in Figure b), as this is consistent with a transition from extracting silver from dry silver ores to the massive exploitation of lead ores for their trace amounts of intrinsic silver, such as argentiferous galena deposits at Laurion.

It is difficult to be completely definitive regarding the chronologies of lead production recorded in Greenland ice. The slope in Figure 2 (a) (from the discovery of cupellation to the introduction of coinage) and (b) (the shallow increase in lead production between 1000 and 700 BCE around the time of Phoenician expansion in Iberia) would suggest that lead ores were increasingly smelted from the Bronze Age. This would be consistent with the application of lead to collect silver or silver minerals from progressively lower grade dry silver ores, that is, lead was used to extract silver dispersed in a host rock (e.g., horn silver has around 75 wt% Ag) rather than extracting very low concentrations of silver (argentiferous galena ores have ≈ 0.2 wt% Ag; Wood et al., 2021: tab. 3) from large amounts of lead ore.

Figure 2 (b) indicates a significant increase in lead production to a peak around the time of the Battle of Salamis in 480 BCE. This increase is also found in world lead production after the introduction of coinage (Figure 2, a). This increase is consistent with the massive exploitation of lead ores for silver. Lead production appears to climb to this peak possibly within or before the reign of Peisistratos (561–527 BCE). Attributing this peak solely to lead smelting at Laurion, however, is problematic. For instance, it is possible that the peak could reflect Carthaginian mining in Iberia. However, unlike Iberia, which was exploited successively by the Phoenicians, Carthaginians and Romans, the peak appears to follow the trajectory of Laurion mining, that is, the decrease in lead emissions appears to be consistent with the cessation of mining activities at Laurion during the war between Athens and Sparta (431–404 BCE). This could suggest that this peak, at least in part, reflects the advance of Laurion mining as well as the loss of a workforce and closure of the Laurion mines (Carugati, 2020) during the Peloponnesian War (Figure 2, b).

In effect, Figure 2 is consistent with the view that argentiferous lead ores were recognized for the silver they contained during the sixth century BCE, and the know-how was developed to extract it. It is also consistent with the notion that Athenian Greece capitalized on this knowledge and that the increase to a peak in lead production, and the concomitant increase in silver production it suggests, may not only reflect but also might have provided the stimulus for the constitutional reforms which led to Athenian democracy.

LAURION MINES, ATTIC SILVER COINS AND LEVANTINE SILVER

Another indicator of the first exploitation of lead ores for silver is the absence of archaeological evidence to suggest centralized control at Laurion until the Archaic period (Mussche, 1998: 17–55). Bearing in mind that centralized control would have only become necessary when the full potential of its silver-bearing lead ores was discovered, the dearth of archaeological evidence suggesting any centralized authority would support the notion that this region was considered principally as a source of lead until the Late Archaic Period. The industrial quarter at Thorikos (the coastal north-east of the Laurion area) only provides an archaeological footprint from the fifth century BCE. This absence of *ergasteria* (ore-washeries, cisterns, mine-annexes, living units, etc.) compared with those found in the Classical era could reflect an experimental stage during the Archaic period (Doctor & Van Liefferinge, 2010). Furthermore, if Aristotle's view (Aristotle, 1952: Ath. Pol. 16.7; Sogno, 2000) on Peisistratos is valid, and his reign was really a golden age because he was able to preserve peace both at home and abroad, it is probable that safeguarding would have extended to the silver mines of Laurion once that lead ores had been recognized for the silver they contained.

A Peisistratid chronology for the first exploitation of lead ores at Laurion, however, is not directly supported by LIA conducted on early Greek coins (Gale et al., 1980) (Figure 1, d). Early Greek Attic coins associated with the Peisistratids, the so-called Wappenmünzen coins (*c*.545–510 BCE; Price & Waggoner, 1975), are not generally consistent with argentiferous lead ores at Laurion in terms of both their LIA values (Figure 1, d) (Gale et al., 1980: tab. 6) and compositional signatures (Wood et al., 2021: tab. 5; Gale et al., 1980: tab. 10). Conversely, the slightly later Athenian owl coins from the Asyut hoard (fifth–fourth centuries BCE) are consistent with Laurion and with the view that the Laurion mines were an important source of revenue for Classical Greece (Ardaillon, 1897; Healy, 1978: 133; Conophagos, 1980; Domergue, 2008: 45). In fact, the Athenian coins (Figure 1, d) group tightly within the Laurion ore LIA field (as would be expected for silver and lead derived from the same ore at one location) which would support the view that the argentiferous lead ores at Laurion became only a valuable source of silver for Athens after the exile of Hippias (510 BCE).

However, one of the Wappenmünzen coins in Figure 1 (d), an obol with wheel obverse (Ashmolean Museum; Price & Waggoner, 1975), nestles within the LIA field of Laurion ores and among the later Athenian coins. Furthermore, the gold-to-silver ratio of this coin is commensurate with silver derived from argentiferous galena ores, such as those found at Laurion (Wood et al., 2021: tab. 5; Gale et al., 1980: tab. 10). The compositional and isotopic signature of this Wappenmünzen coin hints at 'pure' Laurion silver, that is, silver derived from silver-bearing lead ores was available to the Peisistradids.

The presence of 'pure' Laurion silver could indicate that silver minted for the Wappenmünzen coins derived from argentiferous lead ores which, in the majority of cases, had been mixed with silver from other locations (perhaps silver from Thrace and Siphnos, or by using lead from various geological regions to extract it—or both). Recent lead isotope research on the various types of silver ore found around the Aegean (Vaxevanopoulos et al., 2022), as well as previous geological studies, indicate the Laurion district belongs to the Cycladic–Pelagonian belt with base and precious metal mineralization in south Evia, Tinos and Siphnos (Skarpelis, 2002), as well as on Euboea, Mykonos, Tinos and Kythnos (Voudouris et al., 2008). This would support the proposition that minting coins was preceded by a period of trade and monetary use of bullion (Kroll, 2008); that is, the wide range of lead isotope values of the Wappenmünzen coins in Figure 1 (d) is potentially because substantial stocks of existing mixed and recycled silver from various sources were minted to make coins before discrete sources of silver were used (Davis, 2014). In effect, it is plausible that the Wappenmünzen coin that lies within the Laurion isotopic field (Figure 1, d) is one end of several mixing lines.

These Archaic chronologies would bring the exploitation of Laurion closer to the later Iron Age hacksilver hoards of the southern Levant (i.e., Miqne-Ekron, *c*. seventh century BCE/*c*.600 BCE; and Ein Gedi, 630–586 BCE) which have LIA and compositional signatures that are consistent with 'pure' silver from galena ores at Laurion (Thompson, 2003; Thompson & Skaggs, 2013) as well as having mixed signatures (Wood et al., 2019: fig. 4). Essentially, if the Levantine silver hoard chronologies are correct, it would suggest that lead ores at Laurion were exploited for silver in the early sixth century BCE, before Attic coinage, presumably for bullion that could be traded, and that some of it ended up as hacksilver in the southern Levant. A peak in lead production at the beginning of the sixth century BCE supports this chronology (Figure 2, b). Furthermore, this provides further evidence for the presence of silver derived from Laurion lead ores in the Wappenmünzen coins: mixed signatures are exactly as one might expect in a state that had been collecting revenues and storing its accumulated wealth over time in silver bullion. This suggests that when the Athenians chose to mint coins, probably around the mid-sixth century BCE (Kroll, 2008), the stocks of metal available for minting would have been mixtures of local silver from Laurion and non-Attic silver from any number of producing centres.

LEAD ARTEFACTS IN GREECE

Another line of enquiry to investigate the exploitation of lead ores for their intrinsic silver is to examine changes in the applications of lead in the mid-first millennium BCE.

Figure 3 plots the numbers of lead figurines recovered at the sanctuary of Artemis Orthia in Sparta on the Peloponnese by their chronology (dated from pottery in the strata where they were recovered) (Wace, 1929: 249–284; Boardman, 1963; Gill & Vickers, 2001: 232; Leger, 2015: tab. 1). Over 100,000 lead figurines (Figure 3, a) have been recovered at this sanctuary and at other sites in Laconia. Although the sanctuary was used from the eighth century BCE until the end of the Artemis cult in the fourth century CE, the figurines date from the eighth century BCE to the end of the fourth century BCE. Figure 3 (b) shows that a peak of 68,822 figurines from strata dated to 570/560–520 BCE (Lakonian III–IV) is followed by a dramatic decrease (10,016 were found from strata dated to 520 BCE?–425 BCE (Lakonian V) and a complete decline of the lead figures after 425 BCE (Lakonian VI) (Gill & Vickers, 2001; Leger, 2015: tab. 1).

These small, flat, votive figurines of cast lead contain silver (0.057%wt Ag; Friend & Thorneycroft, 1929: 105–117), which means that the lead derived from argentiferous lead ores. LIA of the Laconian votives in the Ashmolean collection have shown that the lead they are made of derived

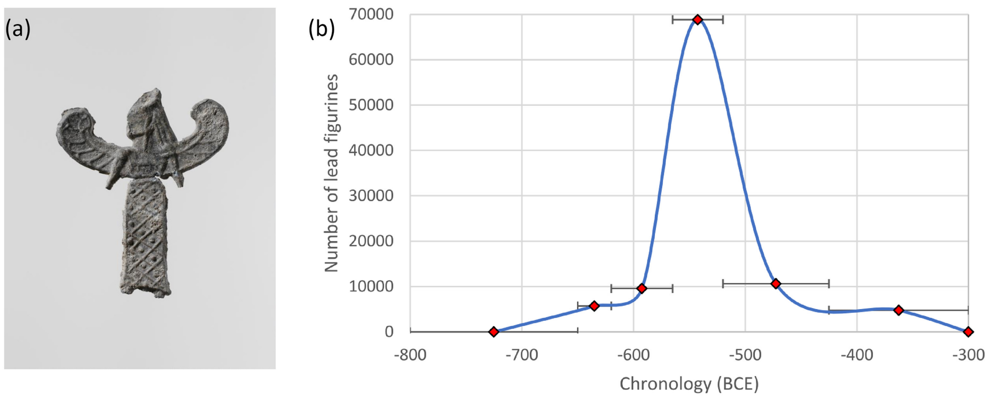

FIGURE 3 (a) Archaic (late seventh–sixth centuries BCE) lead figure of a winged goddess, possibly Artemis Orthia. Height 4.4 cm. The Metropolitan Museum of Art, New York, accession no. 24.195.42. Met. CC0. (b) Numbers of lead figures recovered at Artemis Orthia in Sparta on the Peloponnese, Greece. The peak is between 570/560 and 520 BCE (after Gill & Vickers, 2001: 232; Leger, 2015: tab. 1). [Color figure can be viewed at wileyonlinelibrary.com]

from Laurion (Gill & Vickers, 2001). This would indicate that lead was mined at Laurion and exported in the seventh and sixth centuries BCE.

The patterning in Figure 3 (b) suggests that lead figurines were incredibly popular as offerings in the mid-sixth century BCE. If it is assumed that the numbers of figurines recovered at Artemis Orthia provides a proxy to assess how lead was valued by the Athenians and Spartans, the dramatic decrease around 520 BCE could reflect the Athenians' reluctance to release lead from Laurion because of its silver value; that is, lead ores at Laurion were known for their silver at this time, and possibly earlier if the lead used for the earlier votives was already in circulation in Sparta.

The 520 BCE date for the drop in the numbers of figurines (Figure 3, b) would suggest that restrictions on lead exports were instigated during the reign of Hippias (527–510 BCE). It also suggests that lead ores were not selected at Laurion with regard to their silver concentrations, that is, test smelts to differentiate between lead ores allocated for silver and those for lead—the aforementioned scenario advocated by Gale and Stos-Gale (1981b: 217) and implied by the technical limits proposed for silver extraction in different chronological periods (Rehren & Prange, 1998)—were probably not conducted at this time, or presumably earlier. Moreover, it would also imply that lead was not retrieved routinely from processing debris after the silver had been extracted. This is indicative of a technology in its early stages.

DISCUSSION

Since Ardaillon's (1897) thesis on the mines of Laurion in antiquity, there have been questions over when the silver-bearing lead ore deposits at Laurion were first exploited for silver.

That lead would have been required in the extraction of silver from dry silver ores has often misled researchers into assuming that once native silver and large silver minerals had run out, lead ores were the predominant source of ancient silver. In fact, Laurion, due to the prevalence of its lead isotopic signature in the archaeological record, was considered to have been a significant silver-producing centre in the Bronze Age. However, mid-first millennium BCE chronologies for the exploitation of silver-bearing lead ores better represent the archaeological evidence. The absence of archaeology to suggest any centralized control over Laurion until the Archaic period and the scarcity of silver artefacts recovered in the Late Bronze Age and throughout the Early Iron Age Aegean would suggest that Laurion was not a silver-producing centre until the mid-first millennium BCE. Furthermore, the practice of adding lead to smelt lead-poor silver-bearing ores during the first millennium BCE in Iberia (perhaps following traditions developed during the Bronze Age in Anatolia, Siphnos and Bronze/Iron Age Cyprus) and the seventh century BCE Lydian practice of adding lead to recover silver from production debris after gold parting, suggest that the predominant technology to acquire silver until the late Archaic period was to use lead (often from Laurion) as a silver collector to extract silver from dry silver ores found around the Aegean. In effect, Laurion was probably considered solely as a source of lead until it was discovered that lead ore could be also used as a source of silver in its own right.

A peak in lead pollution in Greenland ice that appears to rise during the sixth century BCE and the emergence of Laurion isotopic signatures in Attic Wappenmünzen coinage and in the late Iron Age hacksilver hoards of the southern Levant suggests that the chronology of this technological transition can be placed perhaps as early as the beginning of the sixth century BCE. This is clearly much later than Bronze Age chronologies that have been proposed previously, but it is also earlier than the archaeological remains of infrastructure and metallurgical debris associated with silver processing at Laurion (fifth–fourth centuries BCE), and the recorded use of silver to pay for the Greek war navy (*c*.480 BCE). Furthermore, these sixth-century BCE chronologies also appear to be supported by a drop in the numbers of lead votive artefacts recovered at Sparta *c*.520 BCE. If this sudden decrease can be interpreted as Athenians placing restrictions on the export of argentiferous lead ores, it would support the position that argentiferous lead ores at Laurion were exploited for silver and that lead metal was reallocated (and not exported) in order to extract its intrinsic silver during the reigns of the Peisistradids.

It is likely that such restrictions would have had repercussions. Once the Athenians recognized that lead ores were a viable source of silver, this news potentially travelled quickly and contributed to the increased tensions between Spartans and Athenian Greeks that were to last for over a century (or officially, until a peace treaty was signed in 1996 CE). In fact, long before Thucydides (Thucydides, 2008: 1.101) reports a planned Spartan attack on Attica in the mid-460s BCE, which aimed to gain control over the silver mines (but was thwarted by an earthquake in Sparta), Cleomenes I (519–490 BCE) of Sparta attacked Attica and Athens in 510 BCE, which resulted in Hippias fleeing to Persia (Berthold, 2002). It is therefore conceivable that Sparta's well-known belligerence toward the growing Athenian Empire became amplified once it was known that lead ores at Laurion were a viable silver source, and that this knowledge is reflected in the dramatic decrease in the numbers of lead votive figurines recovered in Sparta.

Exploitation of lead ores for silver was potentially scaled up when access to Western Mediterranean silver fell into the hands of the Carthaginians (540/535 BCE), when the mines of Siphnos became depleted (*c*. late sixth century BCE) and the Persians first curtailed Athenian access to Thracian silver sources (513/512 BCE), perhaps bringing a supply of skilled miners to Laurion. This would suggest that it is probable Hippias did establish a single, stable and economically minded government which developed a policy for encouraging the demand for Athenian silver in international trade (Kroll, 1981). Furthermore, such a new sector of wealth would have likely shifted the dominance of power from the 'old agriculturally-wealthy elite' (Davis, 2014: 277) to those who had the authority to control sources of lead, build infrastructure and mobilize labour to acquire silver.

The recognition that lead ores could be exploited for their intrinsic silver and its associated technology may have been discovered at Laurion or in other regions with silver sources (such as Thrace or Anatolia). Nonetheless, its introduction at Laurion would have required the labour-intensive stages of finding, mining, beneficiating and smelting large quantities of argentiferous lead ore, followed by cupellation, before silver could be obtained. The Levantine hacksilver and the peak in lead pollution at the beginning of the sixth century BCE (Figure 2, b) suggests that Laurion lead ores may have been exploited from as early as the beginning of the sixth century BCE. If this were the case, however, there was probably not the political resolve at that time for it to continue. Nonetheless, exploitation at Laurion appears to have resumed during the reigns of the Peisistradids, which suggests that Attic Greece was not only a region that had sufficient deposits of argentiferous lead ore but also had the political will at that time to extract silver from them. In effect, when the Athenians found out that silver resided in a familiar and relatively ubiquitous lead mineral, adoption of new silver technology to extract it would have been almost inevitable for a state that could attract, organize, and regulate skilled and unskilled labour, particularly in a climate of conflict and potential invasions.

CONCLUSIONS

Silver had encouraged entrepreneurial trade around the Aegean, the Mediterranean and the Near East to make the mid-first millennium BC look very different to how it had been less than a millennium earlier (Sherratt, 2016). The realization that lead ores at Laurion contained silver and that the scaling-up of known technology could be used to extract it would have been important to Greece at this time because silver was recognized as an exchange standard and a store of value.

Kroll's (1981) suggestion that silver exploitation was expanded at Laurion under the Peisistratids and that Hippias established a government which developed a policy for encouraging the demand for Athenian silver in international trade would appear consistent with the lead pollution records of Greenland ice, lead isotopic analyses of Attic silver coins and hacksilver in the late Iron Age hoards of the southern Levant, as well as being reflected in the numbers of lead votive figurines at sanctuaries in Sparta. In addition to the boost in taxable trade that silver would have generated, Athenian society would have been affected by this new sector, probably to the detriment of the elites that had dominated politics and law during the reigns of the Peisistratids.

Davis (2014: 276) summarizes well the geopolitical aspect of the exploitation of silver when he notes that 'no one could do anything about the money sitting under their feet until certain things happened technically and politically to enable its extraction and sale. The right set of circumstances combined under the Peisistratids which contributed to their wealth and the prosperity of Athens'. It is proposed here that the knowledge and know-how to extract silver from vast amounts of lead was adopted in Greece because this region was predisposed, geologically and politically, to exploit its own argentiferous lead resources, and that the wealth it generated caused changes in power structures which were to lead to the constitutional reforms of Cleisthenes and the birth of democracy. In effect, the knowledge that lead ores at Laurion contained trace levels of silver, and the political resolve to scale-up existing know-how to extract it, resulted in the massive exploitation of lead ores for silver during the sixth century BCE that helped to initiate, fund and protect the radical social experiment that became known as Classical Greece.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the references cited.

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REFERENCES

Anguilano, L., Rehren, T., Müller, W., & Rothenberg, B. (2009). Roman jarosite exploitation at Rio Tinto (Spain). In A. Giumlia-Mair & A. Hauptmann (Eds.). *Archaeometry in Europe II 2007* (pp. 21–29). Associazione Italiana di Metallurgia.

Aperghis, G. (2013). Athenian mines, coins and triremes. *Historia: Zeitschrift für Alte Geschichte*, *62*, 1–24. https://doi.org/10.25162/historia-2013-0001

Ardaillon, E. (1897). *Les Mines du Laurion dans'l'antiquit'*. Nabu Pres.

Aristotle. (1952). *Athēnaiōn politeia (*'Athenian constitution'*, Aristotelian), Aristotle in 23 volumes* (Vol. 20, translated by H. Rackham). Harvard University Press. London, William Heinemann Ltd., Perseus Digital Library, Tufts University. https://www.perseus.tufts.edu/hopper/

Bastin, E. S. (1922). Primary Native Silver Ores near Wickenburg, Arizona, and their Bearing on the Genesis of the Silver Ores of Cobalt, Ontario. Bull. 735, U. S. Geol. Survey, 131–154.

Bell, C., & Wood, J. R. (2022). Reflections on the westward expansion of the Phoenicians in the Early Iron Age: the search for silver and technology transfer. In M. Kõiv, R. Kletter, U. Nõmmik, V. Sazonov, & I. Volt (Eds.). *Responses to the 12th century BC collapse: Recovery and restructuration in the early iron age near east and Mediterranean, Melammu workshop at the University of Tartu (Estonia), 7–9 June 2019*. University of Tartu. (in press).

Berthold, R. M. (2002). The Athenian embassies to Sardis and Cleomen's' invasion of Attica. *Historia: Zeitschrift für Alte Geschichte*, *51*, 259–267.

Boardman, J. (1963). Artemis Orthia and chronology. *Annual of the British School at Athens*, *58*, 1–7. https://doi.org/10.1017/S0068245400013721

Butcher, K., & Ponting, M. (2015). *The metallurgy of Roman silver coinage: From the reform of Nero to the reform of Trajan*. Cambridge University Press.

Candelone, J.-P., Hong, S., Pellone, C., & Boutron, C. F. (1995). Post-industrial revolution changes in large-scale atmospheric pollution of the northern hemisphere by heavy metals as documented in Central Greenland snow and ice. *Journal of Geophysical Research—Atmospheres*, *100*, 16605–16616.

Carugati, F. (2020). Democratic Stability: A Long View. *Annual Review of Political Science*, *23*, 59–75. https://doi.org/10.1146/annurev-polisci-052918-012050

Conophagos, C. (1980). *Le Laurium antique et la technique grécque de la production de'l'argent*. Ekdotike Hellados Athens.

Craddock, P. T. (2000). Reconstruction of the salt cementation process at the Sardis refinery. In E. Ramage & P. T. Craddock (Eds.). *King Croes's' gold: Excavations at Sardis and the history of gold refining* (pp. 200–211). British Museum Press.

Davis, G. (2014). Mining money in late archaic Athens. *Historia: Zeitschrift für Alte Geschichte*, *63*, 257–277. https://doi.org/10.25162/historia-2014-0014
De Jesus, P.S. (1980). *The development of prehistoric mining and metallurgy in Anatolia*. *BAR international series*.
Dickinson, O. (2006). *The Aegean from bronze age to iron age: Continuity and change between the twelfth and eighth centuries BC*. Routledge.
Doctor, R. F., & Van Liefferinge, K. (2010). Thorikos and the Industrial Quarter: A Mine of Information on the Silver Industry of Ancient Attica. In P. Iossif (Ed.). *All that glitters…* (pp. 52–59). The Belgian Contribution to Greek Numismatics.
Domergue, C. (2008). *Les mines antiques: la production des métaux aux époques grecque et romaine*. Picard.
Ellis Jones, J. (1982). The Laurion silver mines: A review of recent researches and results. *Greece and Rome*, *29*, 169–183.
Forbes, R. J. (1950). *Metallurgy in antiquity: A notebook for archaeologists and technologists*. E.J. Brill.
Forsyth, P. Y. (1997). *Thera in the bronze age* (American University studies). Peter Lang.
Friend, J. N., & Thorneycroft, W. E. (1929). The silver content of specimens of ancient and medieval lead. *J. Inst. Metals*, *XLI*, 105–117.
Gale, N. H. (1980). Some aspects of lead and silver mining in the Aegean. In C. Doumas (Ed.). *Thera and the ancient world 2*. London.
Gale, N. H., Gentner, W., & Wagner, G. A. (1980). Mineralogical and Geographical silver sources of archaic Greek coinage. In D. M. Metcalf & W. A. Oddy (Eds.). *Metallurgy in numismatics I* (pp. 3–49). The Royal Numismatics Society.
Gale, N. H., & Stos-Gale, Z. A. (1981a). Lead and silver in the ancient Aegean. *Scientific American*, *244*, 176–193. https://doi.org/10.1038/scientificamerican0681-176
Gale, N. H., & Stos-Gale, Z. A. (1981b). Cycladic lead and silver metallurgy. *Annual of the British School in Athens*, *76*, 169–224. https://doi.org/10.1017/S0068245400019523
Gill, D., & Vickers, M. (2001). Lakonian Lead figurines: Mineral extraction and exchange in the Archaic Mediterranean. *The Annual of the British School at Athens*, *96*, 229–236. https://doi.org/10.1017/S006824540000527X
Healy, J. F. (1978). *Mining and metallurgy in the Greek and Roman world*. Thames and Hudson.
Herodotus. (2007). In R. B. Strassler (Ed.). translated by A.L. Purvis*The landmark Herodotus: The histories*. Pantheon Books: Random House.
Hess, K., Hauptmann, A., Wright, H., & Whallon, R. (1998). Evidence of fourth millennium BC silver production at Fatmali-Kalecik, East Anatolia. *Metallurgica Antiqua*, *8*, 57–67.
Hong, S., Candelone, J.-P., Patterson, C. C., & Boutron, C. F. (1994). Greenland ice evidence of hemispheric Lead pollution two Millenia ago by Greek and Roman civilizations. *Science*, *265*, 1841–1843. https://doi.org/10.1126/science.265.5180.1841
Hong, S., Candelone, J.-P., Patterson, C. C., & Boutron, C. F. (1996a). History of ancient copper smelting pollution during Roman and medieval times recorded in Greenland ice. *Science*, *272*, 246–249. https://doi.org/10.1126/science.272.5259.246
Hong, S., Candelone, J.-P., Soutif, M., & Boutron, C. F. (1996b). A reconstruction of changes in copper production and copper emissions to the atmosphere during the past 7000 years. *The Science of the Total Environment*, *188*, 183–193. https://doi.org/10.1016/0048-9697(96)05171-6
Hopper, R. J. (1968). The Laurion mines: A reconsideration. *Annual of the British School at Athens*, *63*, 293–326. https://doi.org/10.1017/S006824540001443X
Kakavogianni, O., Douni, K., & Nezeri, F. (2008). Silver metallurgical finds dating from the end of the Final Neolithic Period until the Middle Bronze Age in the Area of Mesogeia. In I. Tzachili (Ed.). *Aegean metallurgy in the bronze age: Proceedings of an international symposium held at the University of Crete, Rethymnon, Greece, on November 19–21, 2004* (pp. 45–57). Rethymnon.
Kassianidou, V., & Knapp, A. B. (2005). Archaeometallurgy in the Mediterranean: The social context of mining, technology, and trade. In E. Blake & A. B. Knapp (Eds.). *The archaeology of Mediterranean prehistory* (pp. 215–251). Blackwell.
Kelder, J. M. (2016). Mycenae, Rich in Silver. In K. Kleber & R. Pirngruber (Eds.). *Silver, money and credit. A tribute to Robartus J. van der Spek on the occasion of his 65th birthday on 18th September 2014* (pp. 307–317). Leiden University.
Kitto, H. D. F. (1962). *The Greeks*. Penguin.
Klein, S., & Hauptmann, A. (2016). Ur, Mesopotamia: The lead metal from pit X. *Meta*, *22*(1), 136–140.
Kraay, C. (1976). *Archaic and classical coins*. Methuen.
Kroll, J. H. (1981). From Wappenmünzen to Gorgoneia to owls. *Museum Notes (American Numismatics Society)*, *26*, 1–32.
Kroll, J. H. (2008). Monetary Use of Weighed Bullion in Archaic Greece. In W. Harris (Ed.). *The monetary of the Greeks and romans* (Vol. 36, p. 74). Oxford University Press.
Legarra Herrero, B. (2004). About the distribution of metal objects in Prepalatial Crete. *Papers from the Institute of Archaeology*, *15*, 29–51.
Leger, R. M. (2015). Artemis and her cult, PhD Thesis, University of Birmingham.
McConnell, J. R., Wilson, A. I., Stohl, A., Arienzo, M. M., Chellman, N. J., Eckhardt, S., Thompson, E. M., Pollard, A. M., & Steffensen, J. P. (2018). Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion during antiquity. *PNAS*, *115*, 5726–5731. https://doi.org/10.1073/pnas.1721818115
Merkel, J. (2021). Evidence for the widespread use of dry silver ore in the early Islamic period and its implications for the history of silver metallurgy. *Journal of Archaeological Science*, *135*, 105478. https://doi.org/10.1016/j.jas.2021.105478

Meyers, P. (2003). Production, Distribution, and Control of Silver: Information Provided by Elemental Composition of Ancient Silver Objects. In L. van Zelst (Ed.). *Patterns and process: A festschrift in honor of Dr Edward* (Vol. V. Sayre, pp. 271–288). Smithsonian Institute Press.

Moorey, P. R. S. (1994). *Ancient Mesopotamian materials and industries: The archaeological evidence*. Clarendon.

Murillo-Barroso, M., Montero-Ruiz, I., Rafel, N., Hunt-Ortiz, M. A., & Armada, X.-L. (2016). The macro-regional scale of silver production in Iberia during the first millennium BCE in the context of Mediterranean contacts. *Oxford Journal of Archaeology*, *35*, 75–100. https://doi.org/10.1111/ojoa.12079

Mussche, H. F. (1974). *Thorikos: A guide to the excavation*. Comité des fouilles belges en Grèce.

Mussche, H. F. (1998). *Thorikos. A mining town in ancient Attika*. Comité des fouilles belges en Grèce.

Nezafati, N., & Pernicka, E. (2012). Early silver production in Iran. *Iranian Archaeology*, *3*, 37–45.

OXALID. (2022). Available online <http://oxalid.arch.ox.ac.uk/default.html> accesse½/2/2022.

Papadopoulos, S. (2008). Silver and copper production practices in the prehistoric settlement at Limenaria, Thasos. In I. Tzachili (Ed.). *Aegean metallurgy in the bronze age: Proceedings of an international symposium held at the University of Crete, Rethymnon, Greece, on November 19–21, 2004* (pp. 59–67). Rethymnon.

Patterson, C. C. (1971). Native copper, silver, and gold accessible to early metallurgists. *American Antiquity*, *36*, 286–321. https://doi.org/10.2307/277716

Patterson, C. C. (1972). Silver stocks and losses in ancient and medieval times. *The Economic History Review*, *25*, 205–235. https://doi.org/10.2307/2593904

Pernicka, E., & Bachmann, H. G. (1983). Archäometallurgische Untersuchungen zur antiken Silbergewinnung in Laurion: III. Das Verhalten einiger Spurenelemente beim Abtreiben des Bleis. *Erzmetall*, *36*, 592–597.

Pernicka, E., Rehren, T., & Schmitt-Strecker, S. (1998). Late Uruk silver production by cupellation at Habuba Kabira, Syria. In T. Rehren, A. Hauptmann, & J. D. Muhly (Eds.). *Metallurgica Antiqua: In honour of Hans-Gert Bachmann and Robert Maddin* (pp. 123–134). Selbstverlag des Deutschen Bergbau-Museums.

Pernicka, E., & Wagner, G. A. (1985). Die metallurgische Bedeutung von Sifnos im Altertum. In G. A. Wagner, G. Weisgerber, & W. Kroker (Eds.). *Silber, Blei und Gold auf Sifnos: prähistorische und antike Metallproduktion* (pp. 200–211). Verinigung der Freunde von Kunst und Kutur im Bergbau.

Price, M., & Waggoner, N. (1975). *Archaic silver coinage: The Asyut hoard*. V.C. Vecchi.

Price, S., & Thonemann, P. (2010). *The birth of classical Europe: A history from Troy to Augustine*. Viking Penguin.

Rehren, T., & Prange, M. (1998). Lead metal and patina: a comparison. In T. Rehren, A. Hauptmann, & J. D. Muhly (Eds.). *Metallurgica Antiqua: In honour of Hans-Gert Bachmann and Robert Maddin, Der Anschnitt 8* (pp. 183–196). Deutsches Bergbau-Museum.

Rehren, T., Vanhove, D., & Mussche, H. (2002). Ores from the ore washeries in the Lavriotiki. *Metalla (Bochum)*, *9*(1), 27–46.

Settle, D. M., & Patterson, C. C. (1980). Lead in albacore: Guide to Lead pollution in Americans. *Science*, *207*, 1167–1176. https://doi.org/10.1126/science.6986654

Sherratt, S. (2016). Fro" "institution"l" t" "priva"e": traders, routes and commerce from the Late Bronze Age to the Iron Age. In J. C. Moreno Garcia (Ed.). *Dynamics of production in the ancient near east 1300–500BC*. Oxbow Books.

Skarpelis, N. (2002). Geodynamics and evolution of the miocene mineralization in the Cycladi—Pelagonian belt, Hellenides. *Bulletin of the Geological Society of Greece*, *34*, 2191–2206. https://doi.org/10.12681/bgsg.16862

Sogno, C. (2000). The ideal of political moderation in Aristot'e's *Athenaion Politeia*. *Greek, Roman, and Byzantine Studies*, *41*, 331–347.

Stos-Gale, Z. A., & Gale, N. H. (1982). The sources of Mycenaean silver and lead. *Journal of Field Archaeology*, *9*, 467–485.

Strong, D. E. (1966). *Greek and Roman gold and silver plate*. Methuen.

Thompson, C. (2003). Sealed silver in iron age Cisjordan and th' 'inventi'n' of coinage. *Oxford Journal of Archaeology*, *22*, 67–107. https://doi.org/10.1111/1468-0092.00005

Thompson, C., & Skaggs, S. (2013). King Solom'n's silver? Southern Phoenician Hacksilber hoards and the location of Tarshish. *Internet Archaeology*, *35*. https://doi.org/10.11141/ia.35.6

Thucydides. (2008). In R. B. Strassler (Ed.). translated by R. Crawley*The landmark Thucydides: A comprehensive guide to the Peloponnesian war*. Pantheon Books: Random House.

Treister, M. Y. (1996). *The role of metals in ancient Greek history*. Brill.

Vaxevanopoulos, M., Blichert-Toft, J., Davis, G., & Albarède, F. (2022). New findings of ancient Greek silver sources. *Journal of Archaeological Science*, *137*, 105474. https://doi.org/10.1016/j.jas.2021.105474

Voudouris, P., Melfos, V., Spry, P. G., Bonsall, T. A., Tarkian, M., & Solomos, C. (2008). Carbonate-replacement Pb-Zn-Ag ± Au mineralization in the Kamariza area, Lavrion, Greece: Mineralogy and thermochemical conditions of formation. *Mineralogy and Petrology*, *94*, 85–106. https://doi.org/10.1007/s00710-008-0007-4

Wace, A. J. B. (1929). The lead figurines. In R. M. Dawkins (Ed.). *The sanctuary of Artemis at Orthia*. *Supplement to the Journal of Hellenistic Studies 5*. MacMillan.

Weeks, L. (2013). Iranian metallurgy of the fourth millennium BC in its wider technological and cultural contexts. In C. A. Petrie (Ed.). *Ancient Iran and its neighbours: Local developments and long-range interactions in the fourth-millennium BC*, British Institute of Persian Studies (pp. 277–291). Oxford.

Wertime, T. A. (1968). A metallurgical expedition through the Persian desert. *Science*, *159*, 927–935. https://doi.org/10.1126/science.159.3818.927

Wertime, T. A. (1973). The beginnings of metallurgy: A new look. *Science*, *182*, 875–887. https://doi.org/10.1126/science.182.4115.875

Wood, J. R., Charlton, M. J., Murillo-Barroso, M., & Martinón-Torres, M. (2017a). Gold parting, iridium and provenance ancient silver: A reply to Pernicka. *Journal of Archaeological Science*, *86*, 127–130. https://doi.org/10.1016/j.jas.2017.07.005

Wood, J. R., Charlton, M. J., Murillo-Barroso, M., & Martinón-Torres, M. (2017b). Iridium to provenance ancient silver. *Journal of Archaeological Science*, *81*, 1–12. https://doi.org/10.1016/j.jas.2017.03.002

Wood, J. R., Hsu, Y.-T., & Bell, C. (2021). Sending Laurion back to the future: Bronze age silver and source of confusion. *Internet Archaeology*, *56*. https://doi.org/10.11141/ia.56.9

Wood, J. R., & Montero-Ruiz, I. (2019). Semi-refined silver for the silversmiths of the iron age Mediterranean: A mechanism for the elusiveness of Iberian silver. *Trabajos de Prehistoria*, *76*, 272–285. https://doi.org/10.3989/tp.2019.12237

Wood, J. R., Montero-Ruiz, I., & Bell, C. (2020). The origin of the Tel dor hacksilver and the westward expansion of the Phoenicians in the early iron age. *Journal of Eastern Mediterranean Archaeology and Heritage Studies*, *8*, 1–21. https://doi.org/10.5325/jeasmedarcherstu.8.1.0001

Wood, J. R., Montero-Ruiz, I., & Martinón-Torres, M. (2019). From Iberia to the southern Levant: The movement of silver across the Mediterranean in the early iron age. *Journal of World Prehistory*, *32*, 1–31. https://doi.org/10.1007/s10963-018-09128-3

Yahalom-Mack, N., Langgut, D., Dvir, O., Tirosh, O., Eliyahu-Behar, A., Erel, Y., Langford, B., Frumkin, A., Ullman, M., & Davidovich, O. (2015). The earliest Lead object in the Levant. *PLoS ONE*, *10*, e0142948. https://doi.org/10.1371/journal.pone.0142948

Yener, K. A., Sayre, E. V., Joel, E. C., Özbal, H., Barnes, I. L., & Brill, R. H. (1991). Stable Lead isotope studies of central Taurus ore sources and related artifacts from eastern Mediterranean chalcolithic and bronze age sites. *Journal of Archaeological Science*, *18*, 541–577. https://doi.org/10.1016/0305-4403(91)90053-R

Zhou, J. (2010). Process mineralogy of silver ores and applications in flowsheet design and plant optimization. In D. Fragomeni (Ed.). *Proceedings 2010, 42nd annual meeting of the Canadian mineral processors: Held at the Westin hotel, Ottawa, Ontario, Canada, 19th, 20th and 21st, January 2010; 2010 proceedings* (pp. 143–161).

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